



Novel yellow colored flame compositions with superior spectral performance



Ramy Sadek, Mohamed Kassem, Mohamed Abdo, Sherif Elbasuney*

School of Chemical Engineering, Military Technical College, Kobry El-Kobba, Cairo, Egypt

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ABSTRACT

The production of colored flames is the primary purpose of military signaling, projectile tracing, and illuminating devices. Certain elements and compounds when heated to high temperature have the unique property of emitting lines or narrow bands in the visible region (380–780 nm). This study, reports on the development of novel yellow colored flame compositions with enhanced spectral performance in terms of luminous intensity, and color quality to standard Russian yellow tracer. The light intensity and the imprint spectra of developed yellow flares were measured using digital luxmeter and UV–Vis. spectrometer respectively. The main giving of this study is that the light intensity, and color quality of Russian yellow tracer were improved by 287%, and 170% respectively. This was accomplished by means of optimizing the ratio of novel binder to color source using aluminum metal fuel. Aluminum-based formulations were found to maximize the formation of yellow reactive emitting specimens, and to eliminate any interfering incandescent emission resulted from MgO. Quantification of yellow color emitting specimens in the combustion gaseous products was achieved using chemical equilibrium thermodynamic code named ICT (Institute of Chemical Technology in Germany, Virgin 2008); in an attempt to judge the light quality. This improvement in yellow flare performance established the rule that the emission intensity increases as the reaction temperature increases. In the meantime upper limit of temperature was avoided to maximize the color quality.

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1. Introduction

Pyrotechnic compositions have wide range of applications including gas generator, smoke, noise, heat, and colored flame [1–5]. The production of bright light with single wave length is the primary purpose of colored flame compositions [6–8]. Certain elements and compounds when heated to high temperature have the unique property of emitting lines or narrow bands of light in the visible region (380–780 nm) [9–13]. These elements are called the color source, for instance strontium (red), barium (green), copper (green or blue), and sodium (yellow) [14–17]. Strontium, barium, and copper emit color by forming their halides; this emission type is known as molecular emission which is characterized by broad band emission [18]. In the meantime, atomic emission is characterized by sharp discrete wave length [19,20]. The production of a

vividly colored flame is a challenging problem which need a delicate balance between different factors including [21,22].

- 1) An atomic or molecular species that emit the desired wavelength.
- 2) The emitting species must be sufficiently volatile to exist in the vapor state.
- 3) Sufficient heat should be created to produce the excited emitter.
- 4) Heat is necessary to volatilize and excite the emitter.

The combustion wave of colored flame was demonstrated to consist of five distinctive zones as demonstrated in Fig. 1 [23–25].

The vapors of the atomic or the molecular emitting species are excited by the thermal energy of the secondary luminous combustion zone [26]. The excited levels of atoms, or molecules relaxed to the ground state with the emission of the visible light. Yellow flame presents no color problem considering the very strong atomic emission from excited sodium atoms [15,27]. The wavelength of sodium light actually consists of two wavelengths called D lines (D₁ and D₂) [28]. The sodium spectrum is dominated by the

* Corresponding author.

E-mail addresses: s.elbasuney@MTC.edu.eg, sherif_basuney2000@yahoo.com (S. Elbasuney).

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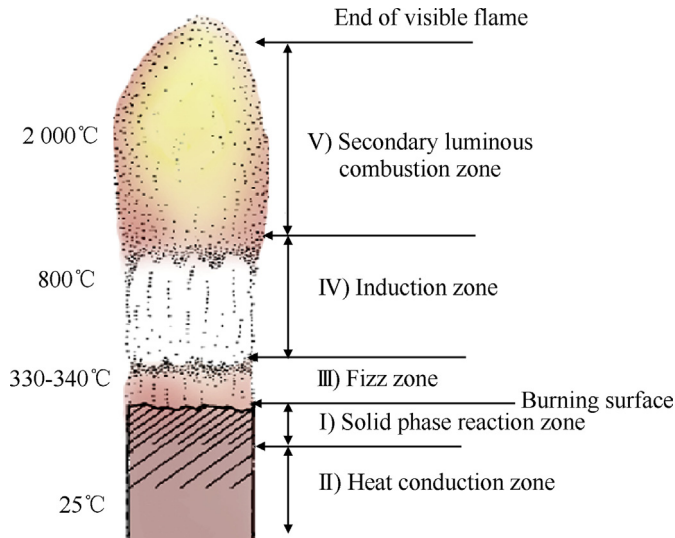


Fig. 1. Distinctive combustions zones of colored flames.

bright doublet known as the sodium D-lines at 584 ± 2 and 588 ± 1 nm [29]. The transition which gives rise to the doublet is from the 3P to the 3S level [30,31]. The 3P level is split into states with total angular momentum $j = 3/2$ and $j = 1/2$ by the magnetic energy of the electron spin in the presence of the internal magnetic field caused by the orbital motion; this effect is called the spin-orbit effect [32]. The difference in energy for the $3P_{3/2}$ and $3P_{1/2}$ is 0.0021 eV (Fig. 2).

Magnesium metal fuel is broadly used in many colored flame compositions. In an oxidizing flame, magnesium is converted to magnesium oxide (MgO), which is an excellent white light emitter by incandescence which may lower the color purity [10,33–36]. In yellow flares the emission intensity at D₁ and D₂ lines increases as the reaction temperature is raised; there is no molecular emitting species to decompose. However, there is an upper limit of temperature that must be avoided for maximum color quality (5000 K) as demonstrated in Fig. 3 [14,37,38].

The chromaticity diagram describes colors in terms of rectangular x and y dimensionless coordinates, further details can be found in the following reference [39]. The pure colors are ranged along the upper edge of the diagram, their wavelengths indicated in

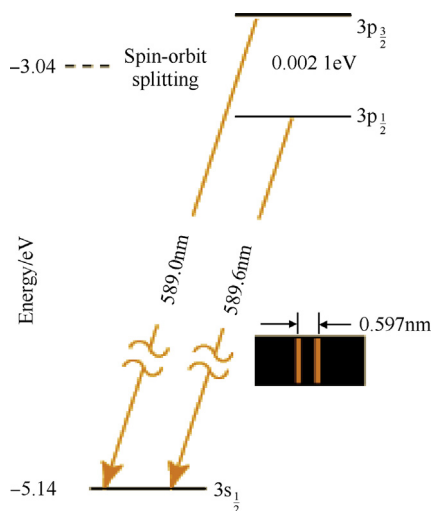


Fig. 2. The sodium doublet energy level diagram.

nm. The colors displayed by sources of blackbody radiation at different temperatures (in kelvin) lie along a line that extends into the center of the diagram [38,40]. As the temperature increases the yellow color fades until 5000 K, above 5000 K the flame becomes white.

The main purpose of this study is to develop yellow flares with enhanced performance, in terms of color quality, color intensity, and duration time. It was possible to enhance light intensity, and color quality of reference flare (Russian yellow e flare) by 287% and 170% respectively. This was achieved mainly by optimizing the ratio of binder to color source using aluminum as a fuel. Quantification of combustion gasses and combustion temperature was accomplished using chemical equilibrium computer program named ICT Thermodynamic Code (Institute of Chemical Technology in Germany, virgin 2008).

2. Experimental work

2.1. Chemicals and materials

The main constituents for yellow flare composition include: oxidizer, metal fuel, color source, binder, and color intensifier. One constituent can have a dual function; NaNO_3 can act as a color source and oxidizer. Table 1 tabulates a list of chemicals used in this study.

2.2. Formulation of yellow colored flame compositions

Russian yellow fire flare was employed as a reference [41] (“see Table 2”). A systematic study to develop enhanced yellow flare was conducted; this study includes the following main steps:

- 1) Fuel rich/stoichiometric formulations ($F_0 - F_1$).
- 2) Type of binder ($F_2 - F_3$).
- 3) Type of fuel (F_4).
- 4) Fuel to oxidizer ratio ($F_5 - F_8$).
- 5) Binder to color source at different fuel types ($F_9 - F_{12}$).

Table 2 summarizes the chemical composition of different investigated formulations.

Manufacture technology should emphasize mixing of different ingredients to the molecular level, good homogenization, and accepted mechanical properties [3]. In this study, the yellow flares were developed through five steps including: sieving of solid particles, intimate mixing, granulation to ensure homogeneity, filling, and pressing. The employed equipments in yellow flare preparation and spectral measurements are scheduled in Table 3.

2.3. Spectral measurements

Photometric tunnels are widely employed to measure the spectral performance of different pyrotechnic devices including: flares, signal, tracer, etc. The employed photometric tunnel dimensions were 8 m (L) \times 2 m (H) \times 0.5 m (W). The distance between the specimen holder and the spectrometer photodetector was 7 m. A schematic of the employed photometric dark tunnel is represented in Fig. 4.

The illuminance (E) was measured using Miltronics DL 1076 digital luxmeter and converted into luminous intensity (I) in candela (cd), by substituting the distance (d) between the light source and the detector in Equation (1) [42]

$$I_{cd} = E_{lx} \times d_m^2 \quad (1)$$

The average luminous intensity (cd/s) was retrieved by

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